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1. PURPOSE

The objective of this calculation is to evaluate the temperature-dependent effective thermal conductivities of a repository-emplaced invert steel set and surrounding ballast materiel. The scope of this calculation analyzes a ballast-material thermal conductivity range of 0.10 to 0.70 W/m·K, a transverse beam spacing range of 0.75 to 1.50 meters, and beam compositions of A 516 carbon steel and plain carbon steel. Results from this calculation are intended to support calculations that identify waste package and repository thermal characteristics for Site Recommendation (SR). This calculation was developed by Waste Package Department (WPD) under Office of Civilian Radioactive Waste Management (OCRWM) procedure AP-3.12Q, Revision 1, ICN 0, *Calculations*.

The references cited in this document are provided in Attachment III (Document Input Reference System [DIRS] database sheets).

2. METHOD

A Finite Element Analysis (FEA) three-dimensional (3-D) representation of the repository invert steel set surrounded with ballast material determines a temperature profile that corresponds to a range of applied heat loads and temperatures. Results from this calculation are applied as inputs to Fourier's Law that governs (one-dimensional [1-D]) heat conduction across a plane, thus generating temperature-dependent anisotropic thermal conductivities. A third-order polynomial curve fit, based on the average temperature of the invert segment, is used to increment the temperature dependence scale. Finally, a third-order polynomial curve fit is applied to the generated outputs to develop an equation for effective thermal conductivity as a function of ballast material thermal conductivity.

3. ASSUMPTIONS

3.1 It is assumed that a rectangular representation of the cross-sectional area of the beam is appropriate for this calculation. Basis: simplifying assumptions are needed in order to develop a case geometry with a reasonable amount of detail. Anisotropic thermal conductivity is largely dependent on the thermal conductivities of the individual materials and the cross-sectional area normal to the flow of heat. Thus, each beam could be represented by a rectangular area equivalent to its cross section (19.1 in^2 [Ref. 13, p. 1-28]). This assumption is used in Section 5.1.1.

3.2 It is assumed that sand filler material is located within all voids of the drift invert structure and up to the top of the steel invert W12X65 beam (see Ref. 2, pp. 1-2). Basis: though it is expected, through the course of filler placement, that pockets of space will exist in and around the components of the steel invert structure, predictions of this void space are unavailable and too complex to specifically address in the FEA representations used for this calculation. This assumption is used in Section 5.1.1.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE APPROVED FOR QUALITY ASSURANCE (QA) WORK

The FEA computer code used for this calculation is ANSYS Version 5.4 (hereafter called "ANSYS"), which is identified with the Computer Software Configuration Item (CSCI) 30040 V5.4 and was obtained from Software Configuration Management in accordance with appropriate procedures. ANSYS is a commercially available finite element code and is appropriate for performing thermal analysis of WPs, WP emplacements, and WP environments as utilized in this calculation. ANSYS is located on a Hewlett-Packard Visualize J2240 server. Calculations using ANSYS V5.4 software were executed on Hewlett-Packard workstations (see References 3, 4, 5, and 6 for complete listing of computers). Software qualification of ANSYS V5.4, including problems of the type analyzed in this report, is summarized in the *Software Qualification Report for ANSYS V5.4, A Finite Element Code* (Ref. 3). The evaluations performed in this calculation are fully within the range of the validation for the ANSYS Version 5.4 code used. Access to and use of the code was granted and performed in accordance with the appropriate procedures. Inputs and outputs to the ANSYS software are included as attachments and are described in the following documentation.

4.2 SOFTWARE ROUTINES

None used.

4.3 MODELS

None used.

5. CALCULATION

When converting values from English to metric units, the added digits of significance are an artifact of the conversion process and do not reflect actual precision of the value as expressed in metric.

5.1 METHODOLOGY

Determining the effective thermal conductivity of the invert structure and surrounding ballast material gives finite element code the ability to better predict the invert material and drift wall temperature histories in repository scale evaluations. In addition, this process characterizes the invert steel set and ballast material as one homogeneous unit, thus simplifying the finite element mesh structure and reducing computation time. Three steps are required to determine values for effective thermal conductivity. They are 1) use finite element code to predict the temperature profile of the invert with applied heat and temperature conditions, 2) use Fourier's Law to calculate the thermal conductivity of the representation, and 3) curve fit the data into tabular format.

This calculation divides the repository invert into two sections (see Figure 5-1). The upper section (also called "block") contains a combination of steel and ballast materials and has a thickness equivalent to the depth of the steel set lateral and axial beams. The lower section is homogeneous and has ballast material properties. The lower section requires an explicate representation in repository scale finite element/difference calculations. Since this is a homogeneous region, there is no further mention of this section of the invert.

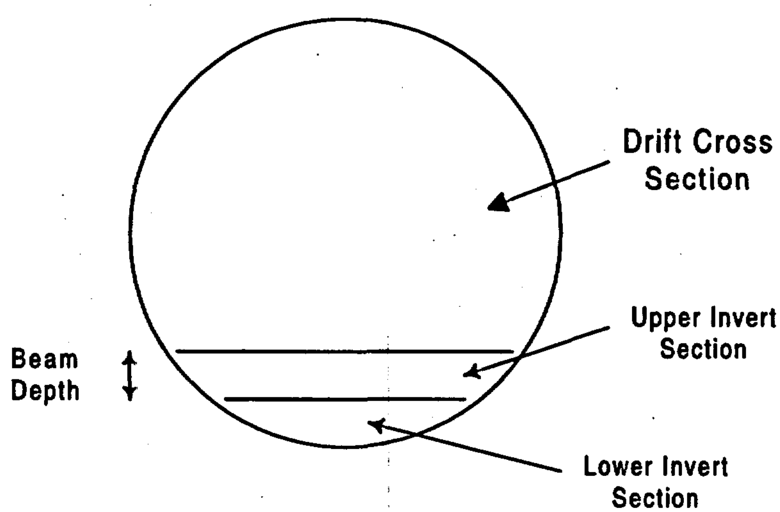

Figure 5-1. Drift Cross Section Showing Upper and Lower Invert Sections

5.1.1 Invert Structure Thermal Representation Development

The ANSYS thermal representation shown in Figure 5-2 is comprised of the steel invert set and the invert ballast material. The steel invert set (see Ref. 2) is made of carbon-steel beams of type W12X65 arranged in lateral and axial relationships to the drift and mounted to the lower side of the drift. Reference 2 indicates that transverse beams have a 1.5-meter separation and axial beams have a 1.0-meter separation. To extend this further, this calculation analyzes transverse beam separations of 0.75, 1.00, 1.25, and 1.5 meters. Beam dimensions are from page 1-28 of Reference 13.

Referring to Figure 5-2, the ANSYS representation simplified the beam as a rectangle with a cross-sectional area equivalent to the actual beam (see Assumption 3.1). This ensures that conductive heat-transfer is appropriately accounted for in the direction taken into consideration while simplifying the ANSYS geometry.

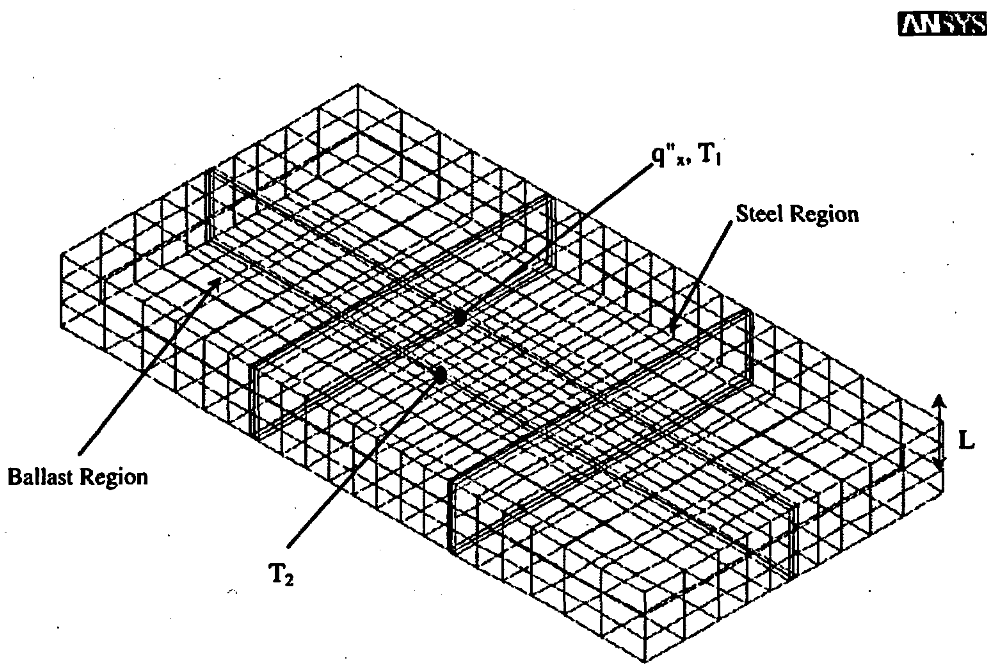

Figure 5-2. ANSYS Representation of the Geometry (Vertical Direction)

The ballast material that is used in this calculation is assumed to be crushed tuff with unknown thermal conductivity. Thus, a range of thermal conductivities, 0.1 - 0.7 W/m·K, is evaluated. Values for the density and specific heat of this material type, as provided in Section 5.2, are representative of crushed tuff. However, these values are unnecessary because the calculation is steady state. Density and specific heat make up the thermal capacity of a material and accounts for transient heating only.

The steel set directionalizes the flow of heat, thus, generating anisotropic thermal conductivities. Vertical, lateral, and axial invert configurations are considered to account for each direction of flow. The ANSYS representations for the lateral and axial directions implement symmetric simplifications. Figure 5-3 depicts the lateral evaluation in which the block is cut midway between the axial beams. Likewise, Figure 5-4 depicts the axial evaluation is which the block is cut along the center of the lateral beam. The vertical calculation used the entire block (see Figure 5-2). For these representations, it is assumed that ballast material completely occupies all of the void space between the beams and the drift wall surface (see Assumption 3.2).

Heat and temperature conditions (provided in Table 5-1) dictate the steady-state temperature distribution of the block. These values are chosen in array format to completely represent its thermal behavior. Dividing heat (W) by the surface area of application converts it to heat flux (W/m^2). The remaining planes with no conditions applied are adiabatic with no heat entering or leaving the system. This directionalizes the flow of heat through an area that is normal to the flow.

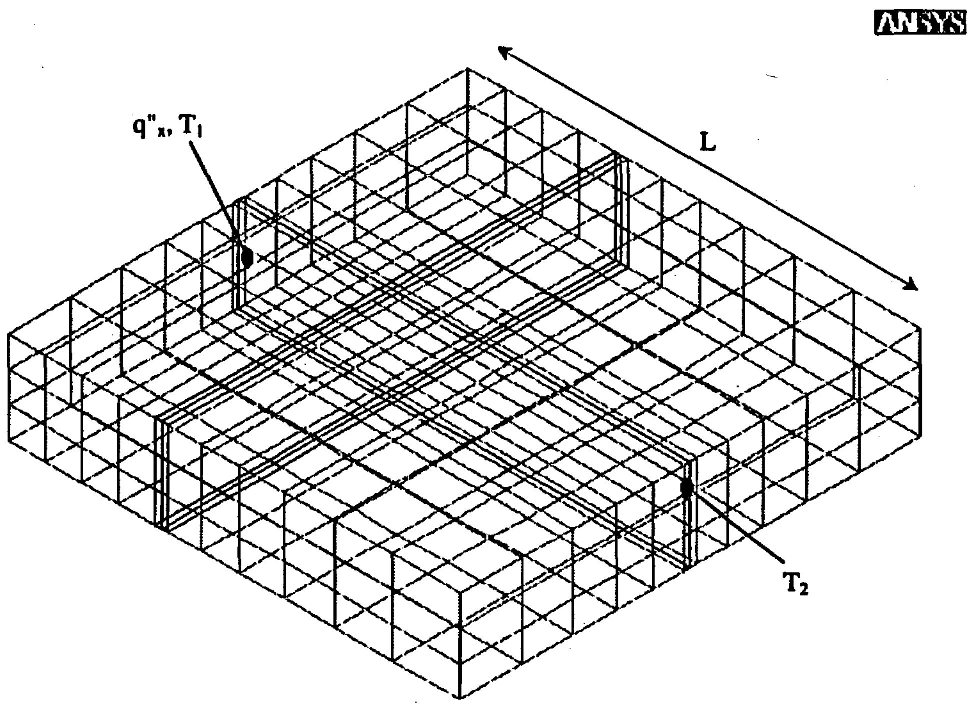

Figure 5-3. ANSYS Representation of the Geometry (Lateral Direction)

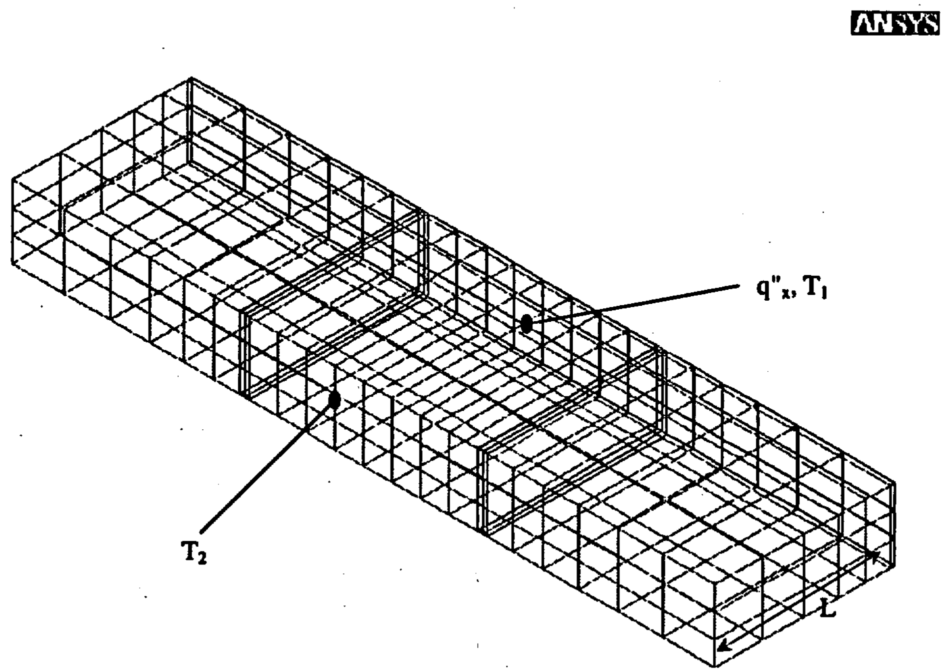

Figure 5-4. ANSYS Representation of the Geometry (Axial Direction)

Table 5-1. Range of Heat and Temperature Conditions

Vertical Evaluation		Lateral Evaluation		Axial Evaluation	
Temperature (°C)	Heat (W)	Temperature (°C)	Heat (W)	Temperature (°C)	Heat (W)
50	1000	50	50	50	50
100	2000	100	100	100	100
150	3000	150	150	150	150
200	4000	200	200	200	200
250	5000	250	250	250	250
300	6000	300	300	300	300
350	7000	350	350	350	350
	8000		400		400
	9000		450		450
	10000		500		500

5.1.2 Calculation for Effective Thermal Conductivity

Effective thermal conductivity is calculated using Equation 5-1 (Ref. 7, p. 4). Inputs to this equation are q''_x, T_1, T_2, and L. Values for heat flux (q''_x) and temperature (T_2) are applied to the ANSYS representations at the planes indicated in Figures 5-2, 5-3, and 5-4. Temperature (T_1) is the average temperature on the indicated block plane, and length (L) is the distance from T_1 to T_2.

$$q''_X = k\frac{T_1 - T_2}{L} \Rightarrow k = \frac{q''_X \cdot L}{T_1 - T_2}$$

(Equation 5-1)

As previously discussed, calculations for thermal conductivity occur with designated heat and temperature loads applied to the representation. To make the thermal conductivity values representative of the temperature that the material is experiencing, coefficients for a third-order curve fit are determined and based on the median temperature of the invert (see Equation 5-2). The resulting equation is solved for a temperature set of 50, 100, 150, 200, 250, 300, and 350 °C.

$$T_m = \frac{T_1 - T_2}{2}$$

(Equation 5-2)

Effective thermal conductivity results exhibit heat independence. This is indicative of the temperature dependence of thermal conductivity. Therefore, thermal conductivity values are averaged over the range of heat loads. Effective thermal conductivity results (based on heat and surface temperature) are provided in Table 5-2 for the axial 1.5-meter spacing, 0.4 W/m·K, and A 516 steel calculation. This table is intended only to show that thermal conductivity and heat are independent.

Table 5-2. Example for Heat - Thermal Conductivity (W/m·K) Independence

Surface Temperature (°C)	Surface Heat (W)									
	50	100	150	200	250	300	350	400	450	500
50	1.428	1.432	1.434	1.435	1.435	1.434	1.432	1.430	1.426	1.423
100	1.438	1.438	1.437	1.435	1.432	1.429	1.425	1.420	1.415	1.410
150	1.435	1.434	1.430	1.426	1.421	1.416	1.410	1.404	1.398	1.391
200	1.425	1.420	1.415	1.409	1.403	1.397	1.390	1.383	1.375	1.367
250	1.407	1.401	1.395	1.387	1.380	1.373	1.365	1.358	1.349	1.341
300	1.385	1.377	1.370	1.362	1.354	1.346	1.338	1.330	1.321	1.312
350	1.359	1.351	1.343	1.335	1.327	1.318	1.309	1.300	1.291	1.281

5.1.3 Curve-fit for Ballast Thermal Conductivity

The thermal conductivities calculated in Section 5.1.2 are distributed over a range of ballast material thermal conductivities of 0.1 through 0.7 W/m·K. A third-order polynomial curve fit for ballast thermal conductivity was performed in Microsoft Excel (see Attachment I) to generate an equation for effective thermal conductivity. Equation 5-3 provides the equation format for the coefficients. Furthermore, the coefficients for this equation are provided in Tables 6-25 and 6-26.

$$K_{eff} = A + B \cdot K_B + C \cdot K_B^2 + D \cdot K_B^3$$

(Equation 5-3)

Where:

K_{eff} = Anisotropic effective thermal conductivity (W/m·K)

K_B = Ballast material thermal conductivity (W/m·K).

5.2 MATERIAL PROPERTIES

The thermal properties are input to ANSYS within the ANSYS input deck. Input decks are provided in Reference 8. The file listing for this reference is available in Attachment II.

Table 5-3 lists the density of A 516 carbon steel. The density of A 516 (C-Mn-Si) is from page 9 of Reference 9.

Table 5-4 lists the thermal conductivity and specific heat of A 516 carbon steel. Values for thermal conductivity and thermal diffusivity of A 516 are from page 600 of Reference 10 and are converted to conductivity and specific heat in International System of units (SI). The conversion of thermal diffusivity (defined in Equation 5-4 [Ref. 10, p. 613]) to specific heat requires the density listed in Table 5-3.

$$\textit{Specific Heat}\ (Btu/lb\cdot{}^{o}F) = \frac{\textit{Thermal Conductivity}\ (Btu/hr\cdot ft\cdot{}^{o}F)}{\textit{Density}\ (lb/ft^{3})\times \textit{Thermal Diffusivity}\ (ft^{2}/hr)}$$

(Equation 5-4)

Table 5-3. Density of A 516 Carbon Steel

	Density (kg/m³)
A 516 Carbon Steel	7850

Table 5-4. Thermal Conductivity and Specific Heat of A 516 Carbon Steel

Temperature		Thermal Conductivity	Thermal Diffusivity	Thermal Conductivity	Specific Heat
(°F)	(°C)	(Btu/hr·ft·°F)	(ft²/hr)	(W/m·K)	(J/kg·K)
70	21.11	23.6	0.454	40.84	444.11
100	37.78	23.9	0.443	41.36	460.92
150	65.56	24.2	0.433	41.88	477.48
200	93.33	24.4	0.422	42.23	493.98
250	121.11	24.4	0.414	42.23	503.52
300	148.89	24.4	0.406	42.23	513.45
350	176.67	24.3	0.396	42.06	524.25
400	204.44	24.2	0.386	41.88	535.62
450	232.22	23.9	0.375	41.36	544.50
500	260.00	23.7	0.364	41.02	556.26
550	287.78	23.4	0.355	40.50	563.14
600	315.56	23.1	0.346	39.98	570.38
650	343.33	22.7	0.333	39.29	582.39
700	371.11	22.4	0.320	38.77	598.04
750	398.89	22.0	0.308	38.08	610.24
800	426.67	21.7	0.298	37.56	622.12
850	454.44	21.2	0.286	36.69	633.29
900	482.22	20.9	0.274	36.17	651.67
950	510.00	20.5	0.262	35.48	668.47
1000	537.78	20.0	0.248	34.61	688.98
1050	565.56	19.6	0.237	33.92	706.54

1100	593.33	19.2	0.228	33.23	719.45
1150	621.11	18.7	0.213	32.36	750.06
1200	648.89	18.2	0.197	31.50	789.29
1250	676.67	17.5	0.179	30.29	835.25
1300	704.44	16.7	0.155	28.90	920.48
1350	732.22	15.8	0.119	27.35	1134.34
1400	760.00	15.3	0.077	26.48	1697.59
1450	787.78	15.1	0.154	26.13	837.70
1500	815.56	15.1	0.169	26.13	763.35

Table 5-5 lists the density of plain carbon steel. The density of plain carbon steel is from page 9 of Reference 9.

Table 5-6 lists the thermal conductivity and specific heat of plain carbon steel. Values for thermal conductivity and thermal diffusivity are from page 600 of Reference 10 and are converted to conductivity and specific heat in SI units. The conversion of thermal diffusivity to specific heat is defined in Equation 5-5.

Table 5-5. Density of Plain Carbon Steel

	Density (kg/m^3)
Plain Carbon Steel	7850

Table 5-6. Thermal Conductivity and Specific Heat of Plain Carbon Steel

Temperature		Thermal Conductivity	Thermal Diffusivity	Thermal Conductivity	Specific Heat
(°F)	(°C)	(Btu/hr·ft·°F)	(ft^2/hr)	(W/m·K)	(J/kg·K)
70	21.11	35.1	0.695	60.7	431
100	37.78	34.7	0.674	60.1	440
150	65.56	34.1	0.645	59	452
200	93.33	33.6	0.613	58.2	468
250	121.11	32.9	0.585	56.9	480
300	148.89	32.3	0.561	55.9	492
350	176.67	31.6	0.534	54.7	506
400	204.44	30.9	0.512	53.5	516
450	232.22	30.3	0.495	52.4	523
500	260.00	29.5	0.472	51.1	534
550	287.78	28.8	0.453	49.8	543
600	315.56	28.0	0.433	48.5	552
650	343.33	27.3	0.414	47.2	563
700	371.11	26.6	0.394	46	577
750	398.89	25.9	0.374	44.8	592
800	426.67	25.2	0.355	43.6	606
850	454.44	24.5	0.335	42.4	625
900	482.22	23.8	0.317	41.2	641
950	510.00	23.1	0.301	40	656
1000	537.78	22.4	0.282	38.8	679
1050	565.56	21.6	0.265	37.4	696
1100	593.33	20.9	0.250	36.2	714

1150	621.11	20.2	0.234	35	738
1200	648.89	19.5	0.218	33.7	764
1250	676.67	18.7	0.197	32.4	811
1300	704.44	18.0	0.180	31.2	854
1350	732.22	17.2	0.134	29.8	1100
1400	760.00	16.4	0.082	28.4	1710
1450	787.78	15.9	0.147	27.5	924
1500	815.56	15.7	0.162	27.2	828

Table 5-7 lists the dry bulk density and specific heat of crushed tuff. The dry bulk density of crushed tuff is from Reference 11 for particles sieved between 2.00 through 4.75 mm. The specific heat of crushed tuff (from the Tptpmn rock unit) is from Reference 12. Values for the thermal conductivity of crushed tuff were varied over the range specified in Section 5.1.3.

Table 5-7. Density and Specific Heat of Crushed Tuff

	Dry Bulk Density (kg/m^3)	Specific Heat (J/kg·K)
Crushed Tuff	1150	948

5.3 FINITE ELEMENT DEVELOPMENT

The general method used to develop the ANSYS cases for this calculation is to create a separate input file for each case. A summary of the ANSYS V5.4 results is provided in Section 6.

The basic layout of an ANSYS input file includes the following:

a) Introduce and identify the problem represented, additional files read by the input deck, and what information is contained in the data files used in the input deck.

b) Define the parameters and dimensions that are used repeatedly in the case.

c) Define the element types that are needed to represent the geometry to perform the calculation.

d) Define the representative geometry and mesh structure.

e) Define all radiation surfaces and create the radiation mesh matrix (if necessary).

f) Apply the internal heat loads and the boundary conditions to the appropriate components. If the calculation is transient, heat loads and boundary conditions are applied at each time step.

g) Select the positions where temperature and heat load accumulations are required.

h) Calculate values for effective thermal conductivity using the generated ANSYS results and echo these values to an output file.

6. RESULTS

This section contains the results generated in Section 5. The ANSYS output files generated with this calculation are listed in Attachment II and provided in Reference 8. Note that the table captions in this section represent "thermal conductivity" with the acronym "TC".

In accordance with AP-3.15Q, Revision 1, ICN 1, *Managing Technical Product Inputs*, the following statement is made: "This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database." Note that in accordance with AP-3.12Q, Revision 0, ICN 0, *Calculations*, calculations shall not provide any conclusions.

Table 6-1, Table 6-2, Table 6-3, and Table 6-4 list the temperature-dependent effective thermal conductivity values for the vertical invert section with A 516 carbon steel beams. Values are varied over a range of transverse beam spacings.

Table 6-5, Table 6-6, Table 6-7, and Table 6-8 list the temperature-dependent effective thermal conductivity values for the lateral invert section with A 516 carbon steel beams. Values are varied over a range of transverse beam spacings.

Table 6-9, Table 6-10, Table 6-11, and Table 6-12 list the temperature-dependent effective thermal conductivity values for the axial invert section with A 516 carbon steel beams. Values are varied over a range of transverse beam spacings.

Table 6-13, Table 6-14, Table 6-15, Table 6-16 and list the temperature-dependent effective thermal conductivity values for the vertical invert section with plain carbon steel beams. Values are varied over a range of transverse beam spacings.

Table 6-17, Table 6-18, Table 6-19, Table 6-20 and list the temperature-dependent effective thermal conductivity values for the lateral invert section with plain carbon steel beams. Values are varied over a range of transverse beam spacings.

Table 6-21, Table 6-22, Table 6-23, Table 6-24 and list the temperature-dependent effective thermal conductivity values for the axial invert section with plain carbon steel beams. Values are varied over a range of transverse beam spacings.

Table 6-25 provides curve-fit coefficients for equations defining effective thermal conductivity for the A 516 steel set and 1.50-meter transverse beam spacings. Equation 5-5 is the general equation for these coefficients.

Table 6-26 provides curve-fit coefficients for equations defining effective thermal conductivity for the plain carbon steel set and 1.50-meter transverse beam spacing cases. Equation 5-5 is the general equation for these coefficients.

Table 6-27 provides vertical, lateral, and axial temperature-dependent effective thermal conductivity values for an invert arrangement with a 0.66 W/m·K ballast thermal conductivity, a 1.50-meter transverse beam spacing, and A 516 carbon steel beams.

Table 6-28 provides vertical, lateral, and axial temperature-dependent effective thermal conductivity values for an invert arrangement with a 0.33 W/m·K ballast thermal conductivity, a 1.50-meter transverse beam spacing, and A 516 carbon steel beams.

Table 6-1. Vertical Effective TC (W/m·K) Values for 0.75 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	7.292	7.392	7.491	7.591	7.689	7.787	7.886
100	7.369	7.469	7.569	7.668	7.768	7.866	7.965
150	7.371	7.471	7.571	7.670	7.770	7.869	7.967
200	7.308	7.408	7.508	7.608	7.707	7.806	7.904
250	7.194	7.294	7.394	7.493	7.592	7.691	7.789
300	7.040	7.140	7.240	7.339	7.438	7.537	7.635
350	6.858	6.958	7.057	7.157	7.255	7.354	7.452

Table 6-2. Vertical Effective TC (W/m·K) Values for 1.0 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	7.071	7.173	7.274	7.375	7.476	7.576	7.676
100	7.153	7.255	7.357	7.458	7.559	7.660	7.760
150	7.157	7.259	7.361	7.463	7.564	7.665	7.766
200	7.096	7.199	7.301	7.403	7.504	7.605	7.705
250	6.984	7.087	7.189	7.290	7.391	7.492	7.592
300	6.833	6.936	7.037	7.139	7.240	7.341	7.441
350	6.657	6.759	6.860	6.962	7.063	7.163	7.263

Table 6-3. Vertical Effective TC (W/m·K) Values for 1.25 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	7.000	7.104	7.206	7.308	7.410	7.511	7.612
100	7.085	7.187	7.290	7.392	7.494	7.595	7.696
150	7.091	7.194	7.296	7.398	7.500	7.601	7.703
200	7.032	7.135	7.237	7.339	7.441	7.543	7.644
250	6.921	7.024	7.127	7.229	7.331	7.432	7.533
300	6.771	6.874	6.977	7.079	7.181	7.283	7.383
350	6.595	6.699	6.801	6.904	7.006	7.107	7.208

Table 6-4. Vertical Effective TC (W/m·K) Values for 1.50 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	6.975	7.078	7.180	7.282	7.384	7.486	7.587
100	7.060	7.163	7.266	7.369	7.471	7.572	7.674
150	7.067	7.170	7.273	7.375	7.477	7.579	7.681
200	7.008	7.111	7.214	7.316	7.418	7.520	7.621
250	6.897	7.001	7.103	7.205	7.307	7.409	7.510
300	6.748	6.852	6.954	7.056	7.158	7.259	7.360
350	6.574	6.678	6.780	6.883	6.985	7.086	7.187

Table 6-5. Lateral Effective TC (W/m·K) Values for 0.75 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.91	2.99	3.07	3.15	3.23	3.31	3.40
100	2.84	2.93	3.01	3.10	3.19	3.29	3.38
150	2.77	2.86	2.96	3.05	3.15	3.25	3.34
200	2.70	2.80	2.90	3.00	3.10	3.20	3.30
250	2.63	2.73	2.84	2.94	3.04	3.14	3.25
300	2.56	2.67	2.77	2.88	2.98	3.08	3.18
350	2.50	2.60	2.70	2.81	2.91	3.02	3.12

Table 6-6. Lateral Effective TC (W/m·K) Values for 1.0 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.284	2.367	2.452	2.540	2.629	2.719	2.811
100	2.239	2.332	2.425	2.521	2.617	2.714	2.811
150	2.192	2.291	2.392	2.492	2.594	2.695	2.797
200	2.143	2.247	2.352	2.456	2.561	2.666	2.770
250	2.092	2.200	2.307	2.414	2.520	2.626	2.732
300	2.041	2.150	2.258	2.366	2.473	2.579	2.685
350	1.988	2.098	2.206	2.314	2.420	2.526	2.631

Table 6-7. Lateral Effective TC (W/m·K) Values for 1.25 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.901	1.990	2.082	2.176	2.271	2.368	2.468
100	1.871	1.969	2.069	2.170	2.272	2.374	2.478
150	1.837	1.942	2.048	2.154	2.260	2.366	2.472
200	1.800	1.910	2.020	2.129	2.238	2.346	2.454
250	1.761	1.873	1.985	2.096	2.206	2.315	2.423
300	1.719	1.833	1.946	2.057	2.167	2.276	2.384
350	1.676	1.791	1.902	2.013	2.122	2.230	2.337

Table 6-8. Lateral Effective TC (W/m·K) Values for 1.50 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.640	1.735	1.833	1.933	2.035	2.139	2.246
100	1.619	1.723	1.829	1.935	2.043	2.150	2.259
150	1.594	1.705	1.816	1.927	2.037	2.147	2.257
200	1.565	1.680	1.795	1.908	2.021	2.132	2.242
250	1.533	1.651	1.767	1.881	1.995	2.106	2.216
300	1.498	1.617	1.733	1.848	1.961	2.072	2.182
350	1.461	1.580	1.696	1.810	1.921	2.032	2.141

Table 6-9. Axial Effective TC (W/m·K) Values for 0.75 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	0.964	1.082	1.197	1.309	1.420	1.529	1.637
100	0.973	1.092	1.207	1.320	1.431	1.540	1.648
150	0.973	1.093	1.208	1.321	1.432	1.542	1.650
200	0.966	1.086	1.201	1.314	1.425	1.534	1.642
250	0.953	1.073	1.188	1.301	1.411	1.520	1.628
300	0.936	1.055	1.170	1.282	1.393	1.502	1.609
350	0.915	1.034	1.149	1.261	1.371	1.480	1.587

Table 6-10. Axial Effective TC (W/m·K) Values for 1.0 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.023	1.139	1.253	1.366	1.476	1.586	1.694
100	1.031	1.149	1.264	1.377	1.488	1.598	1.706
150	1.031	1.149	1.264	1.378	1.489	1.599	1.707
200	1.023	1.142	1.257	1.370	1.481	1.591	1.700
250	1.009	1.128	1.243	1.356	1.467	1.577	1.685
300	0.991	1.109	1.224	1.337	1.448	1.557	1.665
350	0.969	1.087	1.202	1.314	1.425	1.534	1.642

Table 6-11. Axial Effective TC (W/m·K) Values for 1.25 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.065	1.178	1.290	1.401	1.511	1.620	1.728
100	1.070	1.186	1.299	1.411	1.522	1.631	1.739
150	1.068	1.185	1.300	1.412	1.523	1.632	1.741
200	1.060	1.177	1.292	1.404	1.515	1.624	1.733
250	1.046	1.163	1.277	1.390	1.500	1.610	1.718
300	1.027	1.144	1.258	1.370	1.481	1.590	1.698
350	1.005	1.121	1.235	1.347	1.457	1.566	1.674

Table 6-12. Axial Effective TC (W/m·K) Values for 1.50 m, A 516 Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.095	1.206	1.316	1.425	1.534	1.642	1.749
100	1.098	1.212	1.324	1.435	1.544	1.653	1.760
150	1.095	1.210	1.323	1.435	1.544	1.653	1.761
200	1.086	1.202	1.315	1.426	1.536	1.645	1.753
250	1.072	1.187	1.301	1.412	1.522	1.630	1.738
300	1.053	1.168	1.281	1.392	1.502	1.610	1.717
350	1.030	1.145	1.258	1.369	1.478	1.586	1.693

Table 6-13. Vertical Effective TC (W/m·K) Values for 0.75 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	10.380	10.480	10.579	10.679	10.778	10.878	10.976
100	10.069	10.169	10.269	10.368	10.467	10.567	10.666
150	9.727	9.827	9.927	10.027	10.126	10.225	10.324
200	9.362	9.462	9.562	9.662	9.761	9.860	9.959
250	8.981	9.081	9.181	9.280	9.379	9.478	9.577
300	8.590	8.690	8.790	8.889	8.988	9.087	9.186
350	8.198	8.298	8.397	8.496	8.595	8.694	8.793

Table 6-14. Vertical Effective TC (W/m·K) Values for 1.0 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	10.070	10.172	10.274	10.375	10.477	10.579	10.680
100	9.771	9.874	9.976	10.077	10.178	10.279	10.380
150	9.441	9.544	9.646	9.747	9.848	9.949	10.049
200	9.087	9.190	9.291	9.393	9.493	9.594	9.695
250	8.717	8.819	8.920	9.022	9.122	9.223	9.324
300	8.337	8.439	8.540	8.641	8.742	8.843	8.943
350	7.955	8.057	8.158	8.259	8.360	8.461	8.562

Table 6-15. Vertical Effective TC (W/m·K) Values for 1.25 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	9.970	10.073	10.176	10.278	10.381	10.483	10.584
100	9.676	9.779	9.882	9.984	10.087	10.189	10.290
150	9.350	9.453	9.556	9.658	9.760	9.862	9.964
200	8.999	9.102	9.205	9.308	9.410	9.511	9.613
250	8.632	8.735	8.837	8.940	9.042	9.144	9.245
300	8.255	8.358	8.460	8.563	8.665	8.766	8.868
350	7.877	7.979	8.082	8.184	8.286	8.387	8.488

Table 6-16. Vertical Effective TC (W/m·K) Values for 1.50 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	9.934	10.037	10.141	10.244	10.348	10.450	10.552
100	9.642	9.745	9.847	9.950	10.052	10.154	10.256
150	9.317	9.421	9.524	9.626	9.728	9.830	9.931
200	8.968	9.072	9.176	9.279	9.381	9.483	9.585
250	8.602	8.706	8.811	8.915	9.018	9.120	9.222
300	8.226	8.330	8.435	8.539	8.644	8.746	8.847
350	7.848	7.951	8.055	8.159	8.264	8.365	8.467

Table 6-17. Lateral Effective TC (W/m·K) Values for 0.75 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	3.964	4.049	4.134	4.218	4.304	4.390	4.477
100	3.781	3.872	3.965	4.057	4.150	4.243	4.337
150	3.607	3.704	3.801	3.899	3.997	4.095	4.193
200	3.442	3.543	3.644	3.745	3.847	3.948	4.049
250	3.287	3.390	3.493	3.596	3.699	3.802	3.905
300	3.140	3.245	3.349	3.452	3.556	3.659	3.762
350	3.003	3.108	3.211	3.315	3.418	3.520	3.622

Table 6-18. Lateral Effective TC (W/m·K) Values for 1.0 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	3.117	3.206	3.295	3.385	3.477	3.570	3.665
100	2.982	3.078	3.175	3.272	3.371	3.470	3.570
150	2.851	2.954	3.056	3.159	3.261	3.364	3.468
200	2.727	2.833	2.938	3.044	3.150	3.255	3.360
250	2.607	2.716	2.823	2.931	3.038	3.144	3.250
300	2.494	2.603	2.711	2.819	2.926	3.032	3.137
350	2.387	2.495	2.603	2.709	2.815	2.920	3.024

Table 6-19. Lateral Effective TC (W/m·K) Values for 1.25 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.595	2.689	2.785	2.881	2.980	3.081	3.183
100	2.489	2.591	2.694	2.797	2.902	3.007	3.112
150	2.386	2.494	2.602	2.709	2.817	2.925	3.032
200	2.286	2.397	2.508	2.619	2.728	2.837	2.946
250	2.189	2.302	2.415	2.526	2.636	2.746	2.854
300	2.096	2.209	2.322	2.433	2.543	2.652	2.759
350	2.007	2.120	2.231	2.341	2.449	2.557	2.664

Table 6-20. Lateral Effective TC (W/m·K) Values for 1.50 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.237	2.337	2.438	2.542	2.648	2.756	2.866
100	2.151	2.259	2.367	2.477	2.587	2.697	2.807
150	2.066	2.180	2.293	2.405	2.518	2.629	2.740
200	1.982	2.099	2.215	2.330	2.443	2.555	2.666
250	1.901	2.019	2.136	2.251	2.365	2.477	2.588
300	1.821	1.940	2.057	2.171	2.284	2.395	2.506
350	1.745	1.862	1.977	2.091	2.202	2.312	2.422

Table 6-21. Axial Effective TC (W/m·K) Values for 0.75 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.326	1.446	1.564	1.680	1.794	1.906	2.017
100	1.291	1.412	1.530	1.645	1.758	1.870	1.981
150	1.251	1.372	1.490	1.605	1.718	1.830	1.940
200	1.209	1.330	1.447	1.562	1.675	1.786	1.895
250	1.164	1.285	1.402	1.516	1.629	1.739	1.849
300	1.118	1.239	1.356	1.470	1.582	1.692	1.801
350	1.073	1.193	1.309	1.423	1.535	1.644	1.753

Table 6-22. Axial Effective TC (W/m·K) Values for 1.0 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.410	1.528	1.645	1.760	1.874	1.986	2.097
100	1.371	1.491	1.608	1.723	1.836	1.948	2.059
150	1.329	1.449	1.566	1.681	1.794	1.906	2.016
200	1.284	1.403	1.520	1.635	1.748	1.859	1.969
250	1.236	1.355	1.472	1.586	1.699	1.810	1.920
300	1.188	1.307	1.423	1.537	1.649	1.760	1.869
350	1.139	1.258	1.374	1.487	1.599	1.709	1.819

Table 6-23. Axial Effective TC (W/m·K) Values for 1.25 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.466	1.582	1.697	1.811	1.923	2.035	2.145
100	1.425	1.543	1.658	1.772	1.885	1.996	2.106
150	1.380	1.498	1.614	1.728	1.841	1.952	2.062
200	1.333	1.451	1.567	1.681	1.793	1.904	2.013
250	1.284	1.402	1.517	1.630	1.742	1.853	1.962
300	1.234	1.351	1.466	1.579	1.690	1.801	1.910
350	1.183	1.300	1.415	1.528	1.639	1.749	1.858

Table 6-24. Axial Effective TC (W/m·K) Values for 1.50 m, Carbon Steel Beam

Temperature (°C)	Ballast Material Thermal Conductivity (W/m·K)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.507	1.621	1.734	1.846	1.957	2.067	2.177
100	1.463	1.579	1.693	1.806	1.917	2.028	2.137
150	1.417	1.533	1.648	1.760	1.872	1.982	2.092
200	1.368	1.485	1.599	1.712	1.823	1.933	2.042
250	1.318	1.434	1.548	1.660	1.771	1.881	1.990
300	1.266	1.382	1.496	1.608	1.718	1.828	1.936
350	1.214	1.330	1.443	1.555	1.665	1.774	1.882

Table 6-25. Curve-fit Coefficients for A 516 Steel Set, 1.50 Meter

		1.50-Meter Transverse Beam Spacing						
		50	100	150	200	250	300	350
Vertical	A	6.871512	6.956467	6.963025	6.904432	6.79393	6.644763	6.470176
	B	1.036829	1.038152	1.038263	1.037971	1.038086	1.039417	1.042772
	C	-0.02821	-0.01902	-0.01776	-0.02127	-0.02641	-0.03005	-0.02904
	D	0.009346	-0.0006	-0.0017	0.002076	0.006719	0.008239	0.002643
Lateral	A	1.546928	1.515855	1.482899	1.448445	1.412877	1.37658	1.339939
	B	0.915311	1.024757	1.108073	1.167851	1.20668	1.227152	1.231857
	C	0.133032	0.071825	0.01234	-0.04354	-0.09392	-0.13693	-0.17066
	D	-0.02049	-0.028	-0.02265	-0.00752	0.01431	0.039766	0.065767
Axial	A	0.983741	0.983057	0.977731	0.967912	0.953749	0.935391	0.912988
	B	1.121042	1.16213	1.18477	1.193828	1.194167	1.190652	1.188146
	C	-0.04247	-0.09313	-0.1234	-0.13857	-0.14391	-0.14469	-0.14619
	D	0.004132	0.027046	0.041828	0.050441	0.054845	0.057004	0.058878

Table 6-26. Curve-fit Coefficients for Plain Carbon Steel Set, 1.50 Meter

		1.50-Meter Transverse Beam Spacing						
		50	100	150	200	250	300	350
Vertical	A	9.83183	9.537603	9.212318	8.863241	8.497639	8.122781	7.745934
	B	1.019228	1.044179	1.053359	1.050849	1.040733	1.027095	1.014019
	C	0.054595	-0.04554	-0.06376	-0.0301	0.025388	0.072646	0.081627
	D	-0.05893	0.027442	0.037773	0.001962	-0.05009	-0.08847	-0.08328
Lateral	A	2.140745	2.04472	1.952519	1.864251	1.780024	1.699947	1.624128
	B	0.953302	1.059314	1.136375	1.187722	1.216595	1.226232	1.21987
	C	0.140223	0.063886	-0.00282	-0.05925	-0.10479	-0.13881	-0.16067
	D	-0.03254	-0.03015	-0.0186	-0.00056	0.021308	0.044325	0.065824
Axial	A	1.392345	1.346233	1.298557	1.24953	1.199364	1.148274	1.096473
	B	1.154096	1.180753	1.194291	1.198495	1.197154	1.194054	1.192983
	C	-0.05099	-0.09005	-0.11335	-0.12527	-0.13017	-0.13242	-0.13638
	D	0.004584	0.024347	0.03665	0.043503	0.046914	0.048889	0.051438

Table 6-27. Values for 0.66 W/m·K Ballast TC (W/m·K) and A 516 Carbon Steel Beams

	1.50-Meter Transverse Beam Spacing		
Temperature (°C)	Vertical	Lateral	Axial
50	7.546	2.203	1.706
100	7.633	2.215	1.717
150	7.640	2.213	1.718
200	7.581	2.198	1.710
250	7.470	2.172	1.695
300	7.320	2.138	1.675
350	7.146	2.098	1.650

Table 6-28. Values for 0.33 W/m·K Ballast TC (W/m·K) and A 516 Carbon Steel Beams

	1.50-Meter Transverse Beam Spacing		
Temperature (°C)	Vertical	Lateral	Axial
50	7.211	1.863	1.349
100	7.297	1.861	1.357
150	7.304	1.849	1.357
200	7.245	1.829	1.347
250	7.134	1.801	1.334
300	6.985	1.768	1.315
350	6.811	1.730	1.291

7. ATTACHMENTS

The list of attachments is provided in Table 7-1.

Table 7-1. Supporting Documentation

Attachment Number	Description	Size
I	Effective Thermal Conductivity Curve-fit (File Names: Results_A516.xls and Results_CarbonSteel.xls	6 pages
II	Contents of *ANSYS Output Files for Invert Effective Thermal Conductivity Calculation* (Ref. 8) (File name: outfiles.doc)	7 pages
III	Document Input Reference Sheet (DIRS) (File name: DIRS-WIS-TH-000004-00.doc)	3 pages

Vertical Evaluation with A 516 Steel Beams

0.75-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	7.292	7.392	7.491	7.591	7.689	7.787	7.886
100	7.369	7.469	7.569	7.668	7.768	7.866	7.965
150	7.371	7.471	7.571	7.670	7.770	7.869	7.967
200	7.308	7.408	7.508	7.608	7.707	7.806	7.904
250	7.194	7.294	7.394	7.493	7.592	7.691	7.789
300	7.040	7.140	7.240	7.339	7.438	7.537	7.635
350	6.858	6.958	7.057	7.157	7.255	7.354	7.452

1.00-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	7.071	7.173	7.274	7.375	7.476	7.576	7.676
100	7.153	7.255	7.357	7.458	7.559	7.660	7.760
150	7.157	7.259	7.361	7.463	7.564	7.665	7.766
200	7.096	7.199	7.301	7.403	7.504	7.605	7.705
250	6.984	7.087	7.189	7.290	7.391	7.492	7.592
300	6.833	6.936	7.037	7.139	7.240	7.341	7.441
350	6.657	6.759	6.860	6.962	7.063	7.163	7.263

1.25-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	7.000	7.104	7.206	7.308	7.410	7.511	7.612
100	7.085	7.187	7.290	7.392	7.494	7.595	7.696
150	7.091	7.194	7.296	7.398	7.500	7.601	7.703
200	7.032	7.135	7.237	7.339	7.441	7.543	7.644
250	6.921	7.024	7.127	7.229	7.331	7.432	7.533
300	6.771	6.874	6.977	7.079	7.181	7.283	7.383
350	6.595	6.699	6.801	6.904	7.006	7.107	7.208

1.50-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	6.975	7.078	7.180	7.282	7.384	7.486	7.587
100	7.060	7.163	7.266	7.369	7.471	7.572	7.674
150	7.067	7.170	7.273	7.375	7.477	7.579	7.681
200	7.008	7.111	7.214	7.316	7.418	7.520	7.621
250	6.897	7.001	7.103	7.205	7.307	7.409	7.510
300	6.748	6.852	6.954	7.056	7.158	7.259	7.360
350	6.574	6.678	6.780	6.883	6.985	7.086	7.187

	Temperature (C)	50	100	150	200	250	300	350
Ballast Material Thermal Conductivity (W/mK)	0.1	6.975	7.060	7.067	7.008	6.897	6.748	6.574
	0.2	7.078	7.163	7.170	7.111	7.001	6.852	6.678
	0.3	7.180	7.266	7.273	7.214	7.103	6.954	6.780
	0.4	7.282	7.369	7.375	7.316	7.205	7.056	6.883
	0.5	7.384	7.471	7.477	7.418	7.307	7.158	6.985
	0.6	7.486	7.572	7.579	7.520	7.409	7.259	7.086
	0.7	7.587	7.674	7.681	7.621	7.510	7.360	7.187
Curve-fit Coeff.	A	6.871512	6.956467	6.963025	6.904432	6.79393	6.644763	6.470176
	B	1.036829	1.038152	1.038263	1.037971	1.038086	1.039417	1.042772
	C	-0.02821	-0.01902	-0.01776	-0.02127	-0.02641	-0.03005	-0.02904
	D	0.009346	-0.0006	-0.0017	0.002076	0.006719	0.008239	0.002643

Lateral Evaluation with A 516 Steel Beams

0.75-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.91	2.99	3.07	3.15	3.23	3.31	3.40
100	2.84	2.93	3.01	3.10	3.19	3.29	3.38
150	2.77	2.86	2.96	3.05	3.15	3.25	3.34
200	2.70	2.80	2.90	3.00	3.10	3.20	3.30
250	2.63	2.73	2.84	2.94	3.04	3.14	3.25
300	2.56	2.67	2.77	2.88	2.98	3.08	3.18
350	2.50	2.60	2.70	2.81	2.91	3.02	3.12

1.00-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.284	2.367	2.452	2.540	2.629	2.719	2.811
100	2.239	2.332	2.425	2.521	2.617	2.714	2.811
150	2.192	2.291	2.392	2.492	2.594	2.695	2.797
200	2.143	2.247	2.352	2.456	2.561	2.666	2.770
250	2.092	2.200	2.307	2.414	2.520	2.626	2.732
300	2.041	2.150	2.258	2.366	2.473	2.579	2.685
350	1.988	2.098	2.206	2.314	2.420	2.526	2.631

1.25-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.901	1.990	2.082	2.176	2.271	2.368	2.468
100	1.871	1.969	2.069	2.170	2.272	2.374	2.478
150	1.837	1.942	2.048	2.154	2.260	2.366	2.472
200	1.800	1.910	2.020	2.129	2.238	2.346	2.454
250	1.761	1.873	1.985	2.096	2.206	2.315	2.423
300	1.719	1.833	1.946	2.057	2.167	2.276	2.384
350	1.676	1.791	1.902	2.013	2.122	2.230	2.337

1.50-Meter Beam Spacing — Ballast Material Thermal Conductivity (W/mK)

Temperature (C)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.640	1.735	1.833	1.933	2.035	2.139	2.246
100	1.619	1.723	1.829	1.935	2.043	2.150	2.259
150	1.594	1.705	1.816	1.927	2.037	2.147	2.257
200	1.565	1.680	1.795	1.908	2.021	2.132	2.242
250	1.533	1.651	1.767	1.881	1.995	2.106	2.216
300	1.498	1.617	1.733	1.848	1.961	2.072	2.182
350	1.461	1.580	1.696	1.810	1.921	2.032	2.141

	Temperature (C)	50	100	150	200	250	300	350
Ballast Material Thermal Conductivity (W/mK)	0.1	1.640	1.619	1.594	1.565	1.533	1.498	1.461
	0.2	1.735	1.723	1.705	1.680	1.651	1.617	1.580
	0.3	1.833	1.829	1.816	1.795	1.767	1.733	1.696
	0.4	1.933	1.935	1.927	1.908	1.881	1.848	1.810
	0.5	2.035	2.043	2.037	2.021	1.995	1.961	1.921
	0.6	2.139	2.150	2.147	2.132	2.106	2.072	2.032
	0.7	2.246	2.259	2.257	2.242	2.216	2.182	2.141
Curve-fit Coeff.	A	1.546928	1.515855	1.482899	1.448445	1.412877	1.37658	1.339939
	B	0.915311	1.024757	1.108073	1.167851	1.20668	1.227152	1.231857
	C	0.133032	0.071825	0.01234	-0.04354	-0.09392	-0.13693	-0.17066
	D	-0.02049	-0.028	-0.02265	-0.00752	0.01431	0.039766	0.065767

Axial Evaluation with A 516 Steel Beams

0.75-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	0.964	1.082	1.197	1.309	1.420	1.529	1.637
100	0.973	1.092	1.207	1.320	1.431	1.540	1.648
150	0.973	1.093	1.208	1.321	1.432	1.542	1.650
200	0.966	1.086	1.201	1.314	1.425	1.534	1.642
250	0.953	1.073	1.188	1.301	1.411	1.520	1.628
300	0.936	1.055	1.170	1.282	1.393	1.502	1.609
350	0.915	1.034	1.149	1.261	1.371	1.480	1.587

1.00-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.023	1.139	1.253	1.366	1.476	1.586	1.694
100	1.031	1.149	1.264	1.377	1.488	1.598	1.706
150	1.031	1.149	1.264	1.378	1.489	1.599	1.707
200	1.023	1.142	1.257	1.370	1.481	1.591	1.700
250	1.009	1.128	1.243	1.356	1.467	1.577	1.685
300	0.991	1.109	1.224	1.337	1.448	1.557	1.665
350	0.969	1.087	1.202	1.314	1.425	1.534	1.642

1.25-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.065	1.178	1.290	1.401	1.511	1.620	1.728
100	1.070	1.186	1.299	1.411	1.522	1.631	1.739
150	1.068	1.185	1.300	1.412	1.523	1.632	1.741
200	1.060	1.177	1.292	1.404	1.515	1.624	1.733
250	1.046	1.163	1.277	1.390	1.500	1.610	1.718
300	1.027	1.144	1.258	1.370	1.481	1.590	1.698
350	1.005	1.121	1.235	1.347	1.457	1.566	1.674

1.50-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	1.095	1.206	1.316	1.425	1.534	1.642	1.749
100	1.098	1.212	1.324	1.435	1.544	1.653	1.760
150	1.095	1.210	1.323	1.435	1.544	1.653	1.761
200	1.086	1.202	1.315	1.426	1.536	1.645	1.753
250	1.072	1.187	1.301	1.412	1.522	1.630	1.738
300	1.053	1.168	1.281	1.392	1.502	1.610	1.717
350	1.030	1.145	1.258	1.369	1.478	1.586	1.693

		Temperature (C) 50	100	150	200	250	300	350
Ballast Material Thermal Conductivity (W/mK)	0.1	1.095	1.098	1.095	1.086	1.072	1.053	1.030
	0.2	1.206	1.212	1.210	1.202	1.187	1.168	1.145
	0.3	1.316	1.324	1.323	1.315	1.301	1.281	1.258
	0.4	1.425	1.435	1.435	1.426	1.412	1.392	1.369
	0.5	1.534	1.544	1.544	1.536	1.522	1.502	1.478
	0.6	1.642	1.653	1.653	1.645	1.630	1.610	1.586
	0.7	1.749	1.760	1.761	1.753	1.738	1.717	1.693
Curve-fit Coeff.	A	0.983741	0.983057	0.977731	0.967912	0.953749	0.935391	0.912988
	B	1.121042	1.16213	1.18477	1.193828	1.194167	1.190652	1.188146
	C	-0.04247	-0.09313	-0.1234	-0.13857	-0.14391	-0.14469	-0.14619
	D	0.004132	0.027046	0.041828	0.050441	0.054845	0.057004	0.058878

Vertical Evaluation with Plain Carbon Steel Beams

0.75-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	10.380	10.480	10.579	10.679	10.778	10.878	10.976
100	10.069	10.169	10.269	10.368	10.467	10.567	10.666
150	9.727	9.827	9.927	10.027	10.126	10.225	10.324
200	9.362	9.462	9.562	9.662	9.761	9.860	9.959
250	8.981	9.081	9.181	9.280	9.379	9.478	9.577
300	8.590	8.690	8.790	8.889	8.988	9.087	9.186
350	8.198	8.298	8.397	8.496	8.595	8.694	8.793

1.00-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	10.070	10.172	10.274	10.375	10.477	10.579	10.680
100	9.771	9.874	9.976	10.077	10.178	10.279	10.380
150	9.441	9.544	9.646	9.747	9.848	9.949	10.049
200	9.087	9.190	9.291	9.393	9.493	9.594	9.695
250	8.717	8.819	8.920	9.022	9.122	9.223	9.324
300	8.337	8.439	8.540	8.641	8.742	8.843	8.943
350	7.955	8.057	8.158	8.259	8.360	8.461	8.562

1.25-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	9.970	10.073	10.176	10.278	10.381	10.483	10.584
100	9.676	9.779	9.882	9.984	10.087	10.189	10.290
150	9.350	9.453	9.556	9.658	9.760	9.862	9.964
200	8.999	9.102	9.205	9.308	9.410	9.511	9.613
250	8.632	8.735	8.837	8.940	9.042	9.144	9.245
300	8.255	8.358	8.460	8.563	8.665	8.766	8.868
350	7.877	7.979	8.082	8.184	8.286	8.387	8.488

1.50-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	9.934	10.037	10.141	10.244	10.348	10.450	10.552
100	9.642	9.745	9.847	9.950	10.052	10.154	10.256
150	9.317	9.421	9.524	9.626	9.728	9.830	9.931
200	8.968	9.072	9.176	9.279	9.381	9.483	9.585
250	8.602	8.706	8.811	8.915	9.018	9.120	9.222
300	8.226	8.330	8.435	8.539	8.644	8.746	8.847
350	7.848	7.951	8.055	8.159	8.264	8.365	8.467

	Temperature (C)	50	100	150	200	250	300	350
Ballast Material Thermal Conductivity (W/mK)	0.1	9.934	9.642	9.317	8.968	8.602	8.226	7.848
	0.2	10.037	9.745	9.421	9.072	8.706	8.330	7.951
	0.3	10.141	9.847	9.524	9.176	8.811	8.435	8.055
	0.4	10.244	9.950	9.626	9.279	8.915	8.539	8.159
	0.5	10.348	10.052	9.728	9.381	9.018	8.644	8.264
	0.6	10.450	10.154	9.830	9.483	9.120	8.746	8.365
	0.7	10.552	10.256	9.931	9.585	9.222	8.847	8.467
Curve-fit Coeff.	A	9.83183	9.537603	9.212318	8.863241	8.497639	8.122781	7.745934
	B	1.019228	1.044179	1.053359	1.050849	1.040733	1.027095	1.014019
	C	0.054595	-0.04554	-0.06376	-0.0301	0.025388	0.072646	0.081627
	D	-0.05893	0.027442	0.037773	0.001962	-0.05009	-0.08847	-0.08328

Lateral Evaluation with Plain Carbon Steel Beams

0.75-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	3.964	4.049	4.134	4.218	4.304	4.390	4.477
100	3.781	3.872	3.965	4.057	4.150	4.243	4.337
150	3.607	3.704	3.801	3.899	3.997	4.095	4.193
200	3.442	3.543	3.644	3.745	3.847	3.948	4.049
250	3.287	3.390	3.493	3.596	3.699	3.802	3.905
300	3.140	3.245	3.349	3.452	3.556	3.659	3.762
350	3.003	3.108	3.211	3.315	3.418	3.520	3.622

1.00-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	3.117	3.206	3.295	3.385	3.477	3.570	3.665
100	2.982	3.078	3.175	3.272	3.371	3.470	3.570
150	2.851	2.954	3.056	3.159	3.261	3.364	3.468
200	2.727	2.833	2.938	3.044	3.150	3.255	3.360
250	2.607	2.716	2.823	2.931	3.038	3.144	3.250
300	2.494	2.603	2.711	2.819	2.926	3.032	3.137
350	2.387	2.495	2.603	2.709	2.815	2.920	3.024

1.25-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.595	2.689	2.785	2.881	2.980	3.081	3.183
100	2.489	2.591	2.694	2.797	2.902	3.007	3.112
150	2.386	2.494	2.602	2.709	2.817	2.925	3.032
200	2.286	2.397	2.508	2.619	2.728	2.837	2.946
250	2.189	2.302	2.415	2.526	2.636	2.746	2.854
300	2.096	2.209	2.322	2.433	2.543	2.652	2.759
350	2.007	2.120	2.231	2.341	2.449	2.557	2.664

1.50-Meter Beam Spacing

Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
50	2.237	2.337	2.438	2.542	2.648	2.756	2.866
100	2.151	2.259	2.367	2.477	2.587	2.697	2.807
150	2.066	2.180	2.293	2.405	2.518	2.629	2.740
200	1.982	2.099	2.215	2.330	2.443	2.555	2.666
250	1.901	2.019	2.136	2.251	2.365	2.477	2.588
300	1.821	1.940	2.057	2.171	2.284	2.395	2.506
350	1.745	1.862	1.977	2.091	2.202	2.312	2.422

	Temperature (C)	50	100	150	200	250	300	350
Ballast Material Thermal Conductivity (W/mK)	0.1	2.237	2.151	2.066	1.982	1.901	1.821	1.745
	0.2	2.337	2.259	2.180	2.099	2.019	1.940	1.862
	0.3	2.438	2.367	2.293	2.215	2.136	2.057	1.977
	0.4	2.542	2.477	2.405	2.330	2.251	2.171	2.091
	0.5	2.648	2.587	2.518	2.443	2.365	2.284	2.202
	0.6	2.756	2.697	2.629	2.555	2.477	2.395	2.312
	0.7	2.866	2.807	2.740	2.666	2.588	2.506	2.422
Curve-fit Coeff.	A	2.140745	2.04472	1.952519	1.864251	1.780024	1.699947	1.624128
	B	0.953302	1.059314	1.136375	1.187722	1.216595	1.226232	1.21987
	C	0.140223	0.063886	-0.00282	-0.05925	-0.10479	-0.13881	-0.16067
	D	-0.03254	-0.03015	-0.0186	-0.00056	0.021308	0.044325	0.065824

Axial Evaluation with Plain Carbon Steel Beams

0.75-Meter Beam Spacing	Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
	50	1.326	1.446	1.564	1.680	1.794	1.906	2.017
	100	1.291	1.412	1.530	1.645	1.758	1.870	1.981
	150	1.251	1.372	1.490	1.605	1.718	1.830	1.940
	200	1.209	1.330	1.447	1.562	1.675	1.786	1.895
	250	1.164	1.285	1.402	1.516	1.629	1.739	1.849
	300	1.118	1.239	1.356	1.470	1.582	1.692	1.801
	350	1.073	1.193	1.309	1.423	1.535	1.644	1.753

1.00-Meter Beam Spacing	Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
	50	1.410	1.528	1.645	1.760	1.874	1.986	2.097
	100	1.371	1.491	1.608	1.723	1.836	1.948	2.059
	150	1.329	1.449	1.566	1.681	1.794	1.906	2.016
	200	1.284	1.403	1.520	1.635	1.748	1.859	1.969
	250	1.236	1.355	1.472	1.586	1.699	1.810	1.920
	300	1.188	1.307	1.423	1.537	1.649	1.760	1.869
	350	1.139	1.258	1.374	1.487	1.599	1.709	1.819

1.25-Meter Beam Spacing	Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
	50	1.466	1.582	1.697	1.811	1.923	2.035	2.145
	100	1.425	1.543	1.658	1.772	1.885	1.996	2.106
	150	1.380	1.498	1.614	1.728	1.841	1.952	2.062
	200	1.333	1.451	1.567	1.681	1.793	1.904	2.013
	250	1.284	1.402	1.517	1.630	1.742	1.853	1.962
	300	1.234	1.351	1.466	1.579	1.690	1.801	1.910
	350	1.183	1.300	1.415	1.528	1.639	1.749	1.858

1.50-Meter Beam Spacing	Temperature (C)	Ballast Material Thermal Conductivity (W/mK) 0.1	0.2	0.3	0.4	0.5	0.6	0.7
	50	1.507	1.621	1.734	1.846	1.957	2.067	2.177
	100	1.463	1.579	1.693	1.806	1.917	2.028	2.137
	150	1.417	1.533	1.648	1.760	1.872	1.982	2.092
	200	1.368	1.485	1.599	1.712	1.823	1.933	2.042
	250	1.318	1.434	1.548	1.660	1.771	1.881	1.990
	300	1.266	1.382	1.496	1.608	1.718	1.828	1.936
	350	1.214	1.330	1.443	1.555	1.665	1.774	1.882

	Temperature (C)	50	100	150	200	250	300	350
Ballast Material Thermal Conductivity (W/mK)	0.1	1.507	1.463	1.417	1.368	1.318	1.266	1.214
	0.2	1.621	1.579	1.533	1.485	1.434	1.382	1.330
	0.3	1.734	1.693	1.648	1.599	1.548	1.496	1.443
	0.4	1.846	1.806	1.760	1.712	1.660	1.608	1.555
	0.5	1.957	1.917	1.872	1.823	1.771	1.718	1.665
	0.6	2.067	2.028	1.982	1.933	1.881	1.828	1.774
	0.7	2.177	2.137	2.092	2.042	1.990	1.936	1.882
Curve-fit Coeff.	A	1.392345	1.346233	1.298557	1.24953	1.199364	1.148274	1.096473
	B	1.154096	1.180753	1.194291	1.198495	1.197154	1.194054	1.192983
	C	-0.05099	-0.09005	-0.11335	-0.12527	-0.13017	-0.13242	-0.13638
	D	0.004584	0.024347	0.03665	0.043503	0.046914	0.048889	0.051438

File Listing for *ANSYS Output Files for Invert Effective Thermal Conductivity Calculation.* This compact disk (CD) was generated using a Hewlett Packard CD Writer Plus 7200 compact disk read/write system for personal computers. This CD (Ref. 8) is formatted to be read by any standard CD-ROM drive on an IBM compatible personal computer with a Microsoft operating system.

File Name	File Size (kb)	Date
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i10v075x.parm	21.1	02/09/2000
i10v100x.out	312	02/09/2000
i10v100x.parm	21.1	02/09/2000
i10v125x.out	292	02/09/2000
i10v125x.parm	21.1	02/09/2000
i10v150x.out	286	02/09/2000
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i20v125x.out	290	02/09/2000
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i20v150x.out	284	02/09/2000
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DOCUMENT INPUT REFERENCE SYSTEM

1. Document Identifier No./Rev.:	Change:	Title:
CAL-WIS-TH-000004 Rev. 00		INVERT EFFECTIVE THERMAL CONDUCTIVITY CALCULATION

Input Document			4. Input Status	5. Section Used in	6. Input Description	7. TBV/TBD Priority	8. TBV Due To		
2a.	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section					Unqual.	From Uncontrolled Source	Un-Confirmed
2	CRWMS M&O 1999. *Geometrical and Material Properties of the Steel Invert Structure.* Input Transmittal WP-SSR-99398.T. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991209.0055.	Pages 1-2	TBV-4139	Sections 3, 5.1.1	STEEL INVERT SET REPRESENTATION	3	X	N/A	N/A
3	CRWMS M&O 1998. *Software Qualification Report for ANSYS V5.4, A Finite Element Code.* CSCI: 30040 V5.4. DI: 30040-2003, Rev. 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980609.0847.	Entire	N/A - Reference Only	Section 4.1	Software qualification report for ANSYS V5.4	N/A	N/A	N/A	N/A
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7	Incropera, F.P. and DeWitt, D.P. 1996. *Introduction to Heat Transfer.* 3rd Edition. New York, New York: John Wiley & Sons. TIC: 241057.	Page 4	N/A - Accepted Data (Fact)	Section 5.1.2	One-dimensional heat conduction equation	N/A	N/A	N/A	N/A
8	CRWMS M&O 2000. *ANSYS Output Files for Invert Effective Thermal Conductivity Calculation.* CAL-WIS-TH-000004 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000217.0241.	Entire	N/A - Reference Only	Sections 5.2, 6, 7	ANSYS Output Files	N/A	N/A	N/A	N/A
9	ASTM A 20/A 20M-97a. 1997. *Standard Specification for General Requirements for Steel Plates for Pressure Vessels.* West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 242529.	Page 9	N/A - Accepted Data (Fact)	Section 5.2	Density of carbon steel	N/A	N/A	N/A	N/A
10	ASME (American Society of Mechanical Engineers) 1995. "Materials." Section II of *1995 ASME Boiler and Pressure Vessel Code.* New York, New York: American Society of Mechanical Engineers. TIC: 245287.	Page 600	N/A - Accepted Data (Fact)	Section 5.2	Thermal conductivity and diffusivity of plain carbon steel	N/A	N/A	N/A	N/A
		Page 600	N/A - Accepted Data (Fact)	Section 5.2	Thermal conductivity and diffusivity of A 516 carbon steel	N/A	N/A	N/A	N/A
		Page 613	N/A - Accepted Data (Fact)	Section 5.2	Conversion for Specific Heat	N/A	N/A	N/A	N/A
11	Farber, D. (U.S. Geological Survey) 1998. *Copies of Graphs Data and Worksheet to Enter*	Page 6	TBV-4137	Section 5.2	DENSITY OF CRUSHED TUFF	3	X	N/A	N/A

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12	CRWMS M&O 2000. *Thermal Modeling Parameters by Stratigraphic Unit.* Input Transmittal WP-NEP-99390.T. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000125.0167.	Page 1	TBV-4131	Section 5.2	ROCK LAYER LOCATIONS AND PROPERTIES	3	X	N/A	N/A
13	AISC (American Institute of Steel Construction) 1989. *Manual of Steel Construction, Allowable Stress Design.* 9th Edition. Chicago, Illinois: American Institute of Steel Construction. TIC: 205770.	Page 1-28	N/A - Accepted Data (Fact)	Sections 3, 5.1.1	Dimensions of a W12X65 beam	N/A	N/A	N/A	N/A